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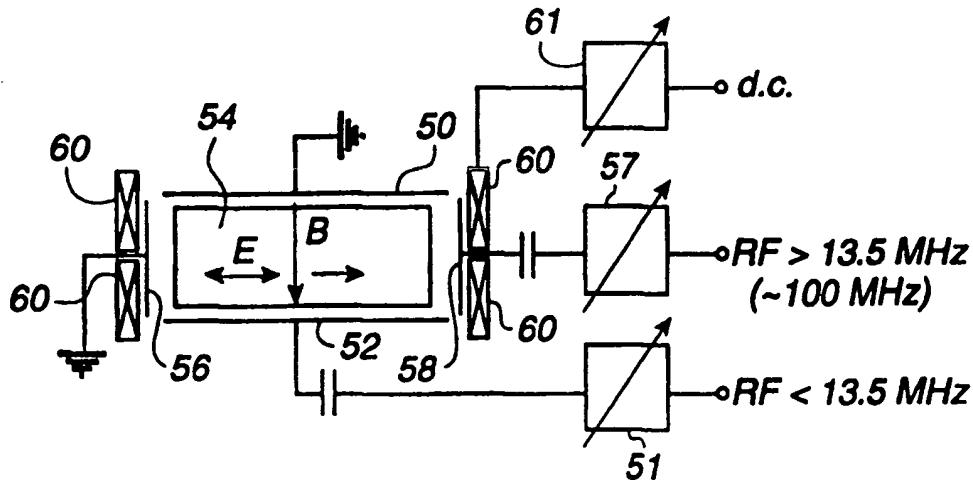


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(54) Title: MAGNETICALLY ENHANCED MULTIPLE CAPACITIVE PLASMA GENERATION APPARATUS AND RELATED METHOD



(57) Abstract

Plasma generation apparatus, and a related method for its operation, for producing a uniform high-density plasma with good process control and process repeatability. The apparatus includes multiple side electrodes (62.1, 62.6) to which first radio-frequency (rf) power source (57) is connected to provide a transverse electric field for plasma generation, and a pair of conventional, upper and lower, electrodes (50, 52) to which a second rf power source (61) is connected to provide separate control of the plasma energy as used in a process such as dry etching. In addition, a magnetic field coil (60) provides a magnetic field perpendicular to the transverse electric field, for enhancement of plasma generation. Because the plasma is generated by a relatively lower frequency (50-200 MHz) power source, as compared with a microwave power source, the magnetic field strength needed to achieve magnetically enhanced operation at or near the electron cyclotron resonance (ECR) condition is well under 100 gauss, which can be provided at relatively low cost. Moreover, the apparatus can be operated efficiently over a relatively wide range of chamber pressures. Ideally, the number of side electrodes used for plasma generation should be four or six, with each electrode receiving a phase delayed signal as compared with an adjacent electrode, to produce a rotating electric field that further enhances uniformity of plasma formation.

MAGNETICALLY ENHANCED MULTIPLE CAPACITIVE PLASMA GENERATION APPARATUS AND RELATED METHOD

BACKGROUND OF THE INVENTION

5 This invention relates generally to plasma generation techniques, particularly as used in a dry etching process in the fabrication of integrated semiconductor devices. In dry etching, process gases are supplied to a vacuum chamber and radio-frequency (rf) energy generates and sustains a plasma cloud within the chamber. Ions in the plasma cloud bombard a workpiece, usually in the form of a semiconductor wafer, which may be
10 located in the chamber immediately adjacent to the plasma, or in a separate processing chamber into which ions from the plasma are drawn. The ions either etch the workpiece or assist the etching, and the etching process may be made selective by patterning a protective coating applied to the workpiece prior to etching.

Various plasma generation techniques have been used and proposed, and specific
15 prior art configurations are discussed further below, with reference to the drawings. In general, however, there are three types of plasma generation approaches: capacitive, inductive, and microwave. In the more conventional capacitive plasma approach, the plasma is formed between a pair of parallel plate electrodes, to which radio-frequency (rf) energy is applied, to one or both plates. A variant of the parallel plate approach is the
20 magnetically enhanced reactive ion etch (MERIE) plasma generation apparatus, in which a magnetic field enhances the formation of ions in the plasma. Both the parallel plate configuration and the MERIE configuration use a single rf power generator.

Inductive plasma generators use an inductive coil, either a planar coil, a cylindrical coil or any of various other types of coils to deliver rf power into the plasma chamber.
25 A separate rf generator supplies energy to at least one plate electrode in the chamber, to control ion energy and direction. The inductive plasma may also employ a magnetic enhancement device, such as a Helicon source.

In magnetically enhanced microwave (MEMW) plasma generators, energy is supplied to the plasma chamber at microwave frequency, through a waveguide. As in the
30 inductive plasma generator, a second power generator supplies rf energy through an electrode plate, to control the plasma. Magnetic enhancement is applied if a high density

apparatus of the invention is a combination of a magnetically enhanced high-frequency rf source, using multiple capacitive plates located at the chamber sidewall, a conventional parallel plate rf source for plasma biasing and control, and a surrounding magnetic coil to provide a magnetic field perpendicular to the rf fields between the multiple capacitive plates.

Briefly, and in general terms, the invention resides in apparatus for use in a plasma chamber having means for introducing plasma process gas and evacuable to preselected operating pressures for processing a substrate at a substrate support face defined by a support within the chamber. The apparatus comprises means for generating a first radio-frequency (rf) electric field in the chamber, referred to as a transverse electric field and directed across the chamber and generally parallel to the substrate support face; means for generating a magnetic field in the chamber generally perpendicular to the first rf electric field; means for generating a second rf electric field generally perpendicular to the first rf electric field; and means for varying at least one of the electric and magnetic fields to control the energy and density of the resulting plasma.

In the disclosed embodiment, the first rf power source operates at a frequency of approximately 13.5 megahertz (MHz) or higher, and the second rf power source operates at a frequency of approximately 13.5 MHz or less. More specifically, the first rf power source operates at a frequency in the range of approximately 50 to 200 MHz, and the second rf power source operates at a frequency in the range of approximately 400 kHz to 13.5 MHz. With the first rf power source operating at a frequency of approximately 200 MHz, the means for generating a magnetic field needs to produce a field strength of less than approximately 100 gauss, for operation at or near an electron cyclotron resonance condition, i.e. a radio-frequency ECR condition.

Preferably, there are n side electrodes, where n is at least four, and the first rf power source includes means for generating n rf signals, delayed from one to the next by a phase angle of $(360/n)^\circ$, for application to the respective side electrodes to produce a rotating electric field in the plasma chamber. The optimum number of side electrodes is probably four or six. More than six adds complexity and cost, but fewer than four side electrodes does not sufficiently enhance the uniformity of plasma generation.

In terms of a novel method, the invention comprises the steps of applying a first

FIG. 6 is a simplified three-dimensional and schematic view of apparatus similar to that shown in FIG. 5, but including three pairs of side electrodes and with a processing chamber downstream of a plasma generation chamber;

5 FIG. 7 is a three-dimensional view similar to FIG. 5, but with two pairs of side electrodes;

FIG. 8 is a schematic view of associated apparatus for generating radio-frequency (rf) power to be applied to the two pairs of side electrodes in the apparatus of FIG. 7;

FIG. 9 is a set of four waveforms of rf power signals generated in the apparatus of FIGS. 7 and 8;

10 FIGS. 10a-10d are diagrams depicting how the apparatus of FIGS. 7 and 8 generate a rotating electric field (E field) vector;

FIG. 11 is a block diagram of a quadrature rf power splitter for use in the apparatus of FIG. 8; and

15 FIG. 12 is a block diagram of an alternative arrangement for generating four rf power signals to be applied to two pairs of side electrodes.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in the drawings for purposes of illustration, the present invention is concerned with a novel technique for generating a plasma suitable for use in plasma 20 processing of workpieces, as in reactive ion etching (RIE) of semiconductor wafers. One form of conventional plasma generation apparatus uses a pair of capacitive parallel plates, indicated at 10 and 12 in FIGS. 1a-1c. Radio-frequency (rf) power is applied to one or both plates through a series capacitor 14.

The parallel plate capacitive configuration is simple, relatively inexpensive to 25 build, and provides relatively good process control and repeatability. Its principal drawback is that it is limited to operation only at relatively high pressures, typically above 100 millitorr. At lower pressures, the mean free path of electrons in the plasma region between the plates is comparable with the distance between the plates, and the plasma density is low. Another important disadvantage is that there is no separate control of the 30 plasma energy. A workpiece (not shown) is typically positioned on the lower electrode 12, and ions in the plasma perform a processing function (etching) as they are drawn to the

means, usually through the top of the chamber, as indicated at 40. A lower frequency rf power source is connected to a lower electrode 42, for plasma control, as in the inductive plasma generators. Magnetic enhancement is provided by field coils, as indicated at 44. These configurations are referred to by the acronym MEMW (magnetically enhanced 5 microwave) plasma generators. If the strength of the magnetic field is appropriately selected, electrons in the plasma gyrate at a frequency in resonance with the microwave frequency, a condition referred to as electron cyclotron resonance (ECR). Alternatively, a slightly different magnetic field strength may be selected, for operation in an "off-resonance" condition.

10 Both inductive and MEMW plasma generators have the advantages of operating at high plasma density and low pressure, and providing separate plasma generation and energy controls. Their disadvantages are that they are complex and expensive, and provide limited process repeatability and control at low pressures.

The present invention has the advantages of both the parallel plate capacitive 15 plasma generator and the inductive and MEMW configurations. The invention retains parallel plate electrodes for plasma energy control, and has magnetic enhancement using a relatively inexpensive magnetic field generator. For plasma generation, the invention uses a first rf generator connected to multiple side electrodes. The basic configuration is shown in FIG. 5. Parallel plate electrodes 50 and 52 are positioned above and below a 20 plasma region 54. A semiconductor wafer (not shown) is held against either the lower electrode 52 or the upper electrode 50. In the configuration shown, the upper electrode 50 is grounded and rf power is applied to the lower electrode 52 to control the plasma. Alternatively, rf power may be applied to both electrodes 50 and 52, through an appropriate rf power splitter (not shown). The frequency of this rf source may be in the 25 range 400 kHz - 13.5 MHz. Rf power to generate the plasma is supplied through side electrodes 56 and 58, one of which is shown as grounded and the other connected to a second rf power source, having a frequency above 13.5 MHz and preferably 50-200 MHz. The electric field generated between the side electrodes 56 and 58 is indicated by vector E. Magnetic field coils 60 are positioned around the plasma chamber, to provide a 30 magnetic field, indicated by vector B, perpendicular to the E field.

The rf power supplied to the side electrodes 56 and 58 is controlled by a power

13.56 MHz	24 cm	1.20×10^3 ev
200 MHz	0.11 cm	5.55 ev
2.45 GHz	7.41×10^{-3} mm	3.70×10^{-2} ev

5 The electron gyration radius r_g is given by the expression:

$$r_g = 2.38 (T_e)^{1/4} B^{-1},$$

where: T_e = electron energy in electron-volts (ev), and

B = magnetic field strength (gauss).

Therefore, the electron gyration radius (in cm) may be calculated as follows for various
10 values of B and T_e :

Electron Energy (ev)	Magnetic Field Strength (gauss)			
	100	200	300	875
10	.075 cm	.038 cm	.025 cm	.0086 cm
20	.106 cm	.053 cm	.035 cm	.012 cm
50	.168 cm	.084 cm	.056 cm	.019 cm
100	.238 cm	.119 cm	.079 cm	.027 cm

One significance of these data is that 875 gauss is the approximate magnetic field
20 strength that is needed to achieve the ECR condition for a microwave plasma generator
operating at a frequency of 2.45 GHz. This can be calculated from the expression for
gyration frequency, which is:

$$f = \frac{eB}{2\pi m}.$$

The magnetic field strength needed to achieve ECR at a frequency of 200 MHz, however,
is only 71.4 gauss. From the table above, the gyration radius values for the 100 gauss
25 field strength are clearly larger than those obtained for 875 gauss, but are still less than
a centimeter. More importantly, it is much less expensive to construct a magnetic field
generator to produce the lower field strength of under 100 gauss, than to construct one

varied in power to control the plasma density, while the plasma energy was controlled by the power supplied to an rf bias electrode. In fact, the power applied to the plasma (the source power) and the power applied to the bias electrode (the bias power) both affect the plasma energy. As the source power is increased, more plasma gas particles are ionized,

5 producing a higher plasma density. However, as the plasma density is increased there is an increase in current through the plasma sheath and a lower associated voltage drop. The dc bias associated with the plasma therefore drops and this is a measure of the energy of ions impinging on the substrate from the plasma. Increasing the bias power also increases the plasma energy. In theory, then, plasma density can be increased by simply increasing

10 the rf plasma source power, without increasing the plasma energy at the same time. However, increasing the plasma source rf power produces high-energy ions, so that increasing the plasma density by increasing the plasma source rf power is accompanied by an unwanted increase in plasma energy.

In the present invention, plasma density is enhanced by increasing the strength of

15 the magnetic field. The magnetic field causes electrons in the plasma to gyrate and produce more collisions, which increases the plasma density without increasing the energy. In fact dc bias, and with it the plasma energy, are reduced as a result of the increased plasma density. In brief, the invention provides three controls over plasma density and energy, and affords more independent control over these parameters.

20 In the embodiment of FIG. 6, there are three pairs of side electrodes, shown at 62.1 - 62.6. As will be discussed with respect to FIGS. 8 and 9, the side electrodes are connected in pairs of diametrically opposed electrodes, with each plate being supplied with an rf signal that is delayed in phase with respect to an adjacent electrode. For six electrodes, the phase delay between adjacent electrodes in the FIG. 6 embodiment is

25 (360/6) $^{\circ}$ or 60 $^{\circ}$. Edges of adjacent electrodes are shown as being parallel with each other, but not parallel with the principal axis of the plasma chamber, to smooth any discontinuities that arise from having abrupt terminations in the electrode surfaces. FIG. 6 also depicts a configuration in which the plasma is utilized in a downstream processing chamber 64. Basically, in designing the specific structure of the processing system the

30 lower electrode may be raised for *in situ* plasma processing, or lowered for downstream processing.

applied to the electrodes 66.1-66.4, respectively. This apparatus includes a master rf power supply 80, and a slave rf power supply 82 that is coupled to the master rf power supply through a 90° phase delay circuit 84. The apparatus further includes two 0°-180° splitters 86 and 88 and two conventional matching networks 90 and 92. Power signals

5 from the rf power supplies 80 and 83 are connected through the matching networks 90 and 92 to respective 0°-180° splitters 86 and 88. Splitter 86 generates rf power signals at angles 0° and 180° for connection to electrodes 66.1 and 66.3, respectively, and splitter 88 generates rf power signals at angles 90° and 270° for connection to electrodes 66.2 and 66.4, respectively.

10 It will be appreciated from the foregoing that the present invention represents a significant advance in the field of plasma generation apparatus. In particular, the invention combines the advantages of conventional parallel plate plasma generation with those of inductive plasma generation. The resulting apparatus can be operated efficiently at either high or low pressures and provides separate plasma control and good process control and
15 repeatability. Moreover, for operation at or near the electron cyclotron resonance (ECR) condition, a much weaker (and therefore less expensive) magnetic field is needed than for operation of a comparable microwave plasma apparatus at the ECR condition. Although a number of embodiments of the invention have been described in detail, it will be understood that various modifications may be made without departing from the spirit and
20 scope of the invention. Accordingly, the invention should not be limited except as by the appended claims.

5 400 kHz to 13.5 MHz.

1 4. Apparatus as defined in claim 2, wherein:
2 the first rf power source operates at a frequency of approximately 50-100 MHz;
3 and
4 the means for generating a magnetic field produces a field strength of less than
5 approximately 100 gauss, for operation at or near an electron cyclotron resonance condi-
6 tion.

1 5. Apparatus as defined in claim 1, wherein:
2 there are n side electrodes, where n is at least four;
3 the first rf power source includes means for generating n rf signals, delayed from
4 one to the next by a phase angle of $360/n$ degrees, for application to the respective side
5 electrodes to produce a rotating electric field in the plasma chamber.

1 6. Apparatus as defined in claim 5, wherein:
2 the number n of side electrodes is four.

1 7. Apparatus as defined in claim 5, wherein:
2 the number n of side electrodes is six.

1 8. A method for operating a plasma chamber having upper and lower electrodes
2 and a sidewall, evacuable to preselected operating pressures, and capable of containing
3 plasma process gasses, the method comprising the steps of:
4 applying a first radio-frequency (rf) power signal to a plurality of side electrodes,
5 disposed about the chamber sidewall, to produce an electric field transverse to the
6 chamber sidewall, for supporting a plasma discharge;
7 generating a magnetic field in the chamber generally perpendicular to the
8 transverse electric field, for enhancing the plasma density; and
9 applying a second rf power signal to a pair of spaced, opposed upper and lower
10 electrodes to produce an electric field in the chamber generally perpendicular to the

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1 14. A method as defined in claim 12, wherein:
2 the number n of side electrodes is six.

1 15. A method for generating a controllable plasma within a plasma processing
2 chamber adapted to be maintained at preselected operating pressures and into which may
3 be introduced process gases for processing a substrate at a substrate support face defined
4 by a support within the chamber, the method comprising the steps of:
5 generating a first radio-frequency (rf) electric field in the chamber across the
6 substrate support face;
7 generating a magnetic field in the chamber transverse to the first rf electric field;
8 generating a second rf electric field transverse to the first rf electric field; and
9 varying at least one of the electric and magnetic fields to control the energy and
10 density of the resulting plasma.

1 16. A method as defined in claim 15, and further including the step of rotating the
2 first rf electric field.

1 17. A method as defined in claim 15, wherein the step of varying one of the
2 electric and magnetic fields includes varying the magnetic field while maintaining the
3 electric fields constant, to obtain a desired plasma density without significantly affecting
4 the plasma energy.

1 18. A method as defined in claim 17, wherein the magnetic field is increased in
2 strength to obtain a desired high plasma density without increasing the plasma energy.

1 19. A method as defined in claim 15, wherein the second rf electric field is
2 generated by capacitively coupling rf power to at least one electrode of a first pair of
3 electrodes positioned generally parallel to and on opposite sides of the substrate support
4 face.

3 electrodes arranged radially symmetrically about the chamber wall.

1 29. Apparatus for use in a plasma chamber evacuable to preselected operating
2 pressures and capable of maintaining a gaseous wafer processing environment, for
3 processing a substrate at a substrate support face defined by a support within the chamber,
4 the apparatus comprising:

5 first electrodes for supporting a first radio-frequency (rf) electric field directed
6 across the substrate support face;
7 at least one magnetic field support device for supporting a magnetic field in the
8 chamber transverse to the first rf electric field;
9 second electrodes for supporting a second rf electric field transverse to the first rf
10 electric field; and
11 a controller to vary at least one of the electric and magnetic fields to control the
12 energy and density of the resulting plasma.

1 30. Apparatus as defined in claim 29, and further including means for rotating the
2 first rf electric field.

1 31. Apparatus as defined in claim 29, wherein the controller varies the magnetic
2 field while maintaining the electric fields constant, to obtain a desired plasma density
3 without significantly affecting the plasma energy.

1 32. Apparatus as defined in claim 31, wherein the controller increases the strength
2 of the magnetic field to obtain a desired high plasma density without increasing the plasma
3 energy.

1 33. Apparatus as defined in claim 29, wherein said second electrodes include a pair
2 which is positioned generally parallel to and on opposite sides of the substrate support
3 face.

1 34. Apparatus as in claim 33, in which at least one electrode of said pair of

3 condition.

1 44. Apparatus as defined in claim 30, wherein the plasma is confined to a radially
2 symmetrical region, and in which said first electrodes comprise a plurality of electrodes
3 arranged radially symmetrically about the chamber wall.

1 45. Apparatus as defined in claim 29, in which said first electrodes direct the first
2 rf electric field generally parallel to the wafer support face.

1 46. Apparatus as defined in claim 29, in which said magnetic field device directs
2 the magnetic field generally perpendicular to the first rf electric field.

1 47. Apparatus as in claim 29, in which said electrodes direct the second rf electric
2 field generally perpendicular to the first rf electric field.

Fig. 1a (Prior Art)

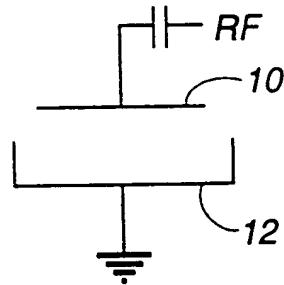


Fig. 2a (Prior Art)

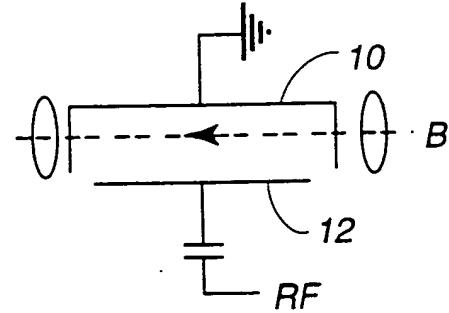


Fig. 1b (Prior Art)

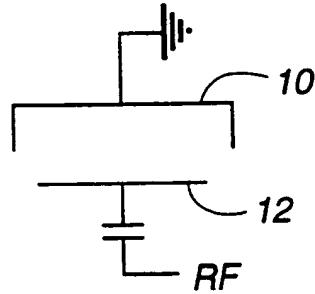


Fig. 2b (Prior Art)

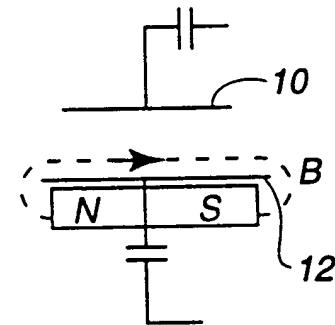


Fig. 1c (Prior Art)

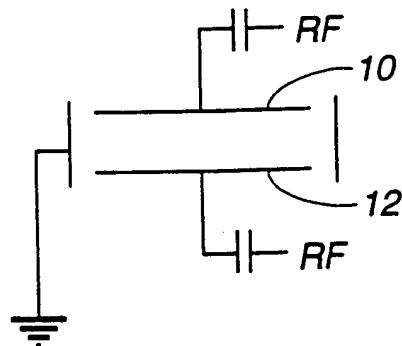


Fig. 2c (Prior Art)

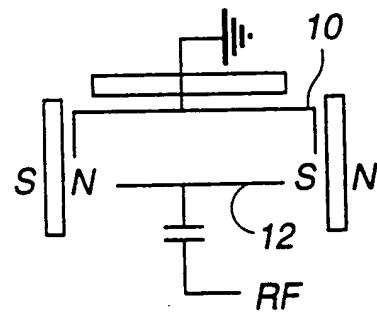


Fig. 3a (Prior Art)

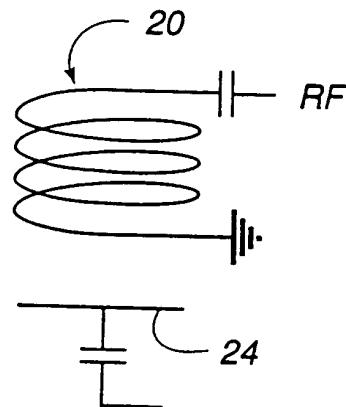


Fig. 4a (Prior Art)

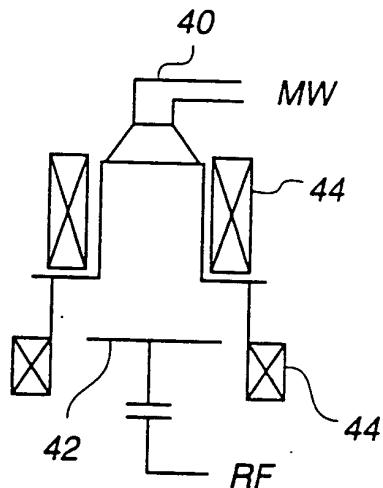


Fig. 3b (Prior Art)

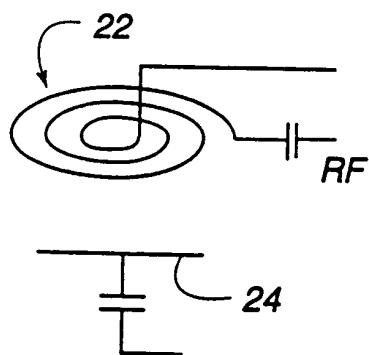


Fig. 4b (Prior Art)

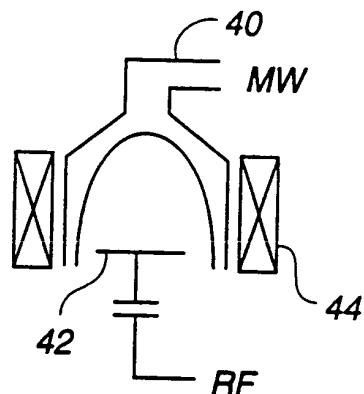


Fig. 3c (Prior Art)

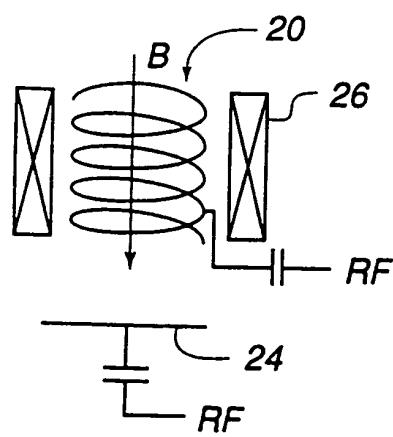
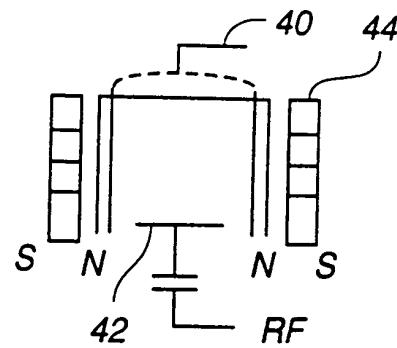


Fig. 4c (Prior Art)



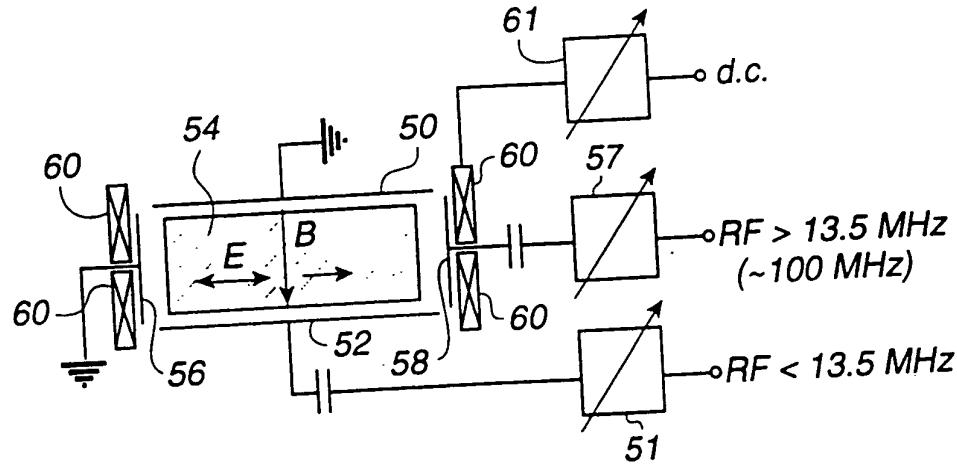


Fig. 5

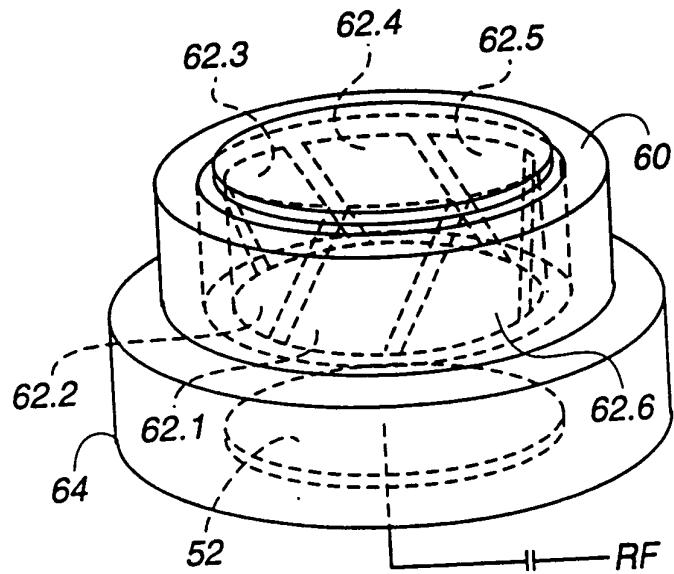


Fig. 6

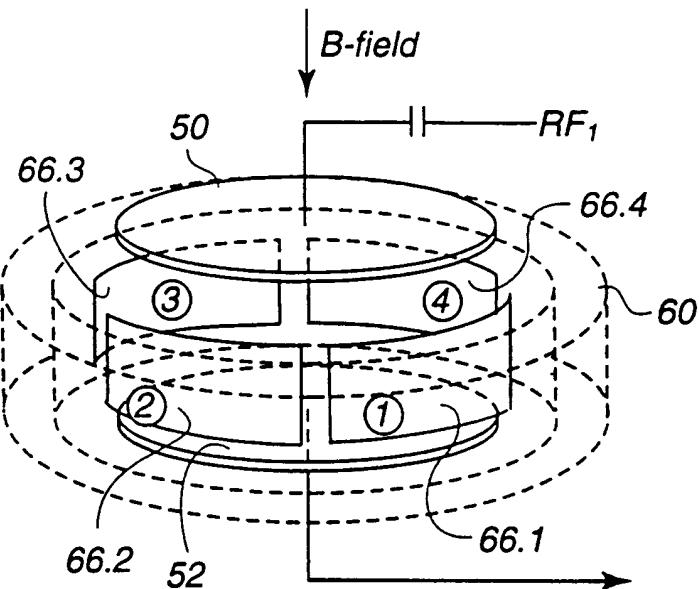


Fig. 7

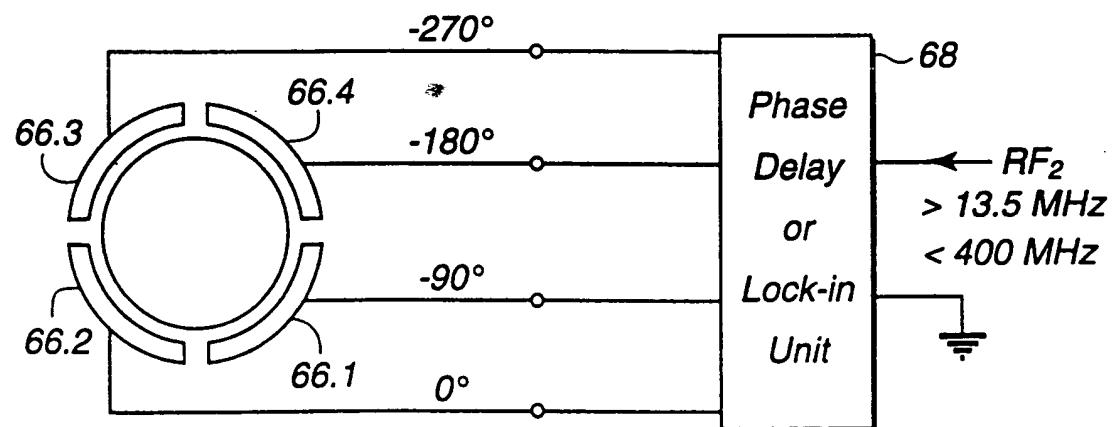


Fig. 8

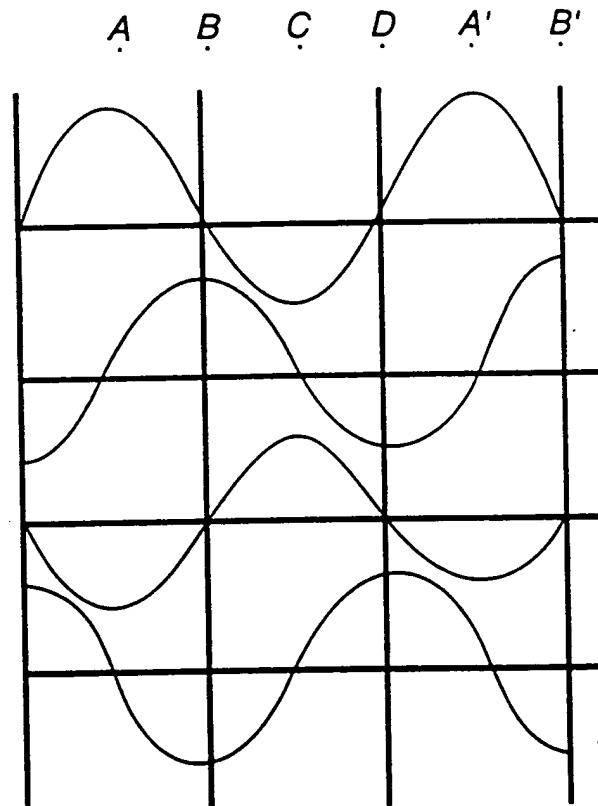


Fig. 9

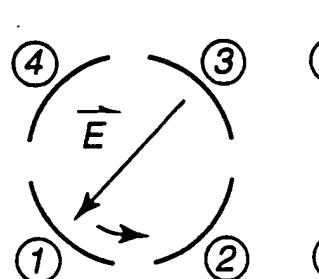


Fig. 10a

Fig. 10b

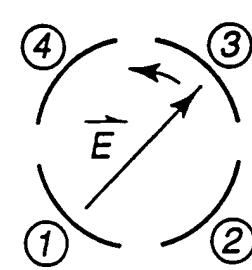
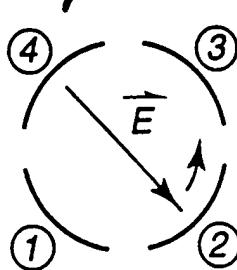
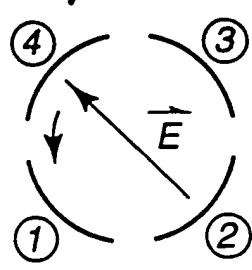


Fig. 10c

Fig. 10d



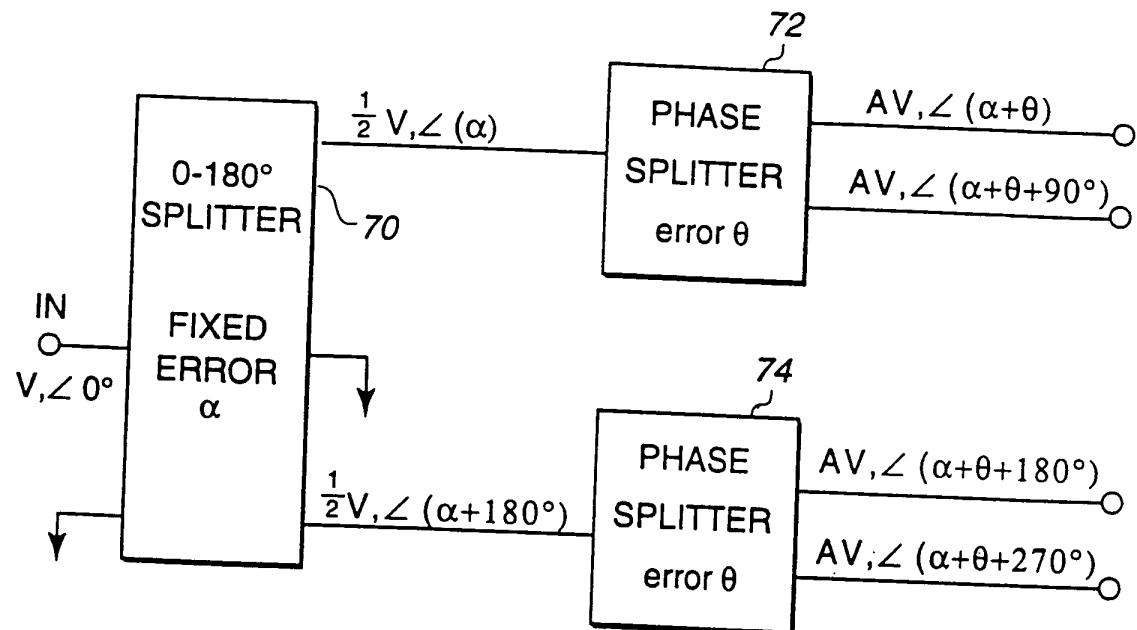


Fig. 11

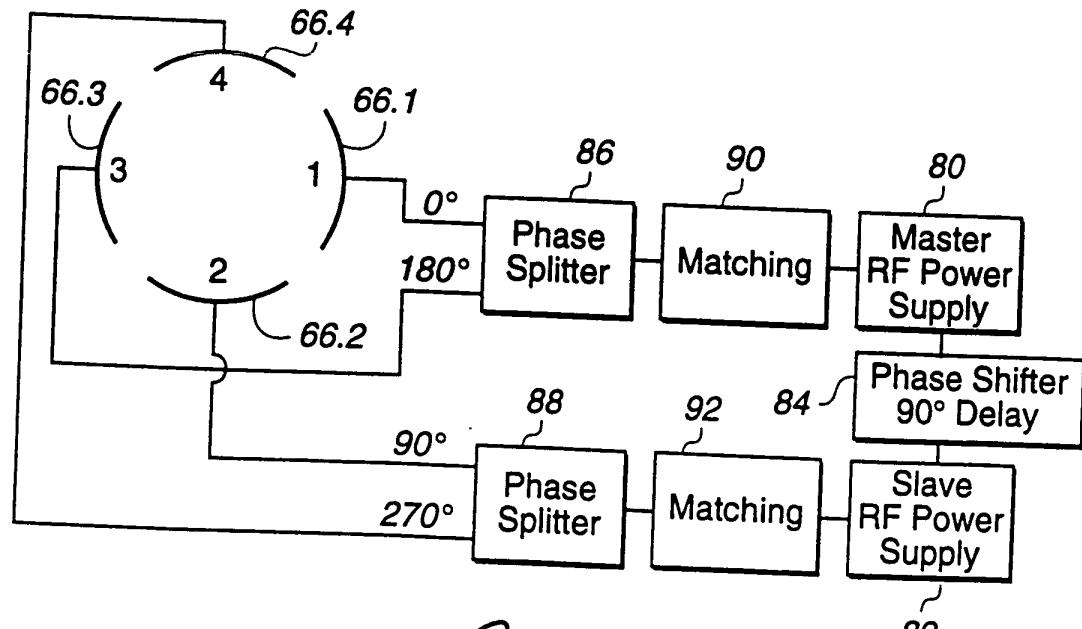


Fig. 12

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US95/06242

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :C23C 16/00; C23F 1/02; C23C 14/00

US CL : 118/723E, 723R 156/345; 204/2298.06, 298.17, 298.18, 298.34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 118/723MP, 723E, 723MA, 723R; 156/345; 204/2298.06, 298.16, 298.17, 298.18, 298.19, 298.2, 298.21, 298.34, 298.37, 298.39

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US, A, 5,330,606 (KUBOTA et al) 19 JULY 1994, Figures 1,28 10; Columns 6-7; Columns 9 & 10; Columns 7, lines 25-35; figures	1-47
Y	US, A, 5,225,024 (HANLEY et al) 06 JULY 1993, Figure 1; abstract.	1-47

 Further documents are listed in the continuation of Box C. See patent family annex.

• Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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